Design for Deconstruction and Materials Reuse

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SUMMARY

The building legacy of the 20th century has been one of waste and toxicity. The US EPA has estimated that the materials debris from building renovation and demolition comprise 25 to 30% of all waste produced in the US each year. Aesthetic conventions and economic factors that influence land use and buildings over long periods of time are not predictable by the building designer, but nonetheless, buildings can be built with the intention of adaptation and / or eventual removal. Design for deconstruction (DfD) can make use of the lessons learned from product design for environment, and from the obstacles encountered in the deconstruction of modern buildings. This paper will discuss principles of design for disassembly and lessons learned from deconstruction practice to propose guidelines for design for deconstruction as a form of environmentally responsible architecture. Although there are three fundamental building types - residential, commercial and industrial, this paper will focus on the generic levels of: whole-building, elements, components, sub-components, and materials.

KEYWORDS: building disassembly; deconstruction; design for deconstruction

INTRODUCTION

Design for deconstruction (DfD) is an emerging concept that borrows from the fields of design for disassembly, reuse, remanufacturing and recycling in the consumer products industries. Its overall goal is to increase resource and economic efficiency and reduce pollution impacts in the adaptation and eventual removal of buildings, and to recover components and materials for reuse, re-manufacturing and recycling. The practice of DfD will allow existing and new building stock to one day serve as the primary source of materials for replacement construction, in effect mining and harvesting existing building stock rather than the natural environment. This resource flow will be encouraged by aging and obsolescent buildings, dwindling natural resources, and declining population in developed countries. The population of Europe as a whole is expected to decline by 7% over the next 50 years (U.S. Census Bureau, 1999).

While the term is new, the foundation of DfD in the latter 20th century includes the work of N. J. Habakren on housing “support” systems, the Open Building movement, and the writings of Stewart Brand on adaptive architecture (Habraken, 1981; Kendall and Teicher, 2000; Brand, 1994). The International Style of architecture developed in the 1940’s, 50’s, and 60’s had attributes that are compatible with DfD such as modular construction, open floor plans, exposed structural and mechanical systems, and the use of concrete, stone, steel, and glass, i.e. recyclable materials. The dynamic technological and economic forces on commercial buildings in general have driven the development of modular and self-contained workstations, raised flooring systems, passive building integrated heating and cooling systems, and finish products that are designed for recycling. By these means, commercial building design has facilitated buildings that enable the disassembly of non-structural components. Whether there is reuse and recycling of the recovered components and materials is a separate matter.

DfD expands upon these commercial building adaptive strategies to consider the whole life-cycle of the building, not just construction and operation, and maintenance and repair, but major adaptations, and eventual whole-building removal from the building's site. If overall "sustainable development" necessitates an increase in the reuse and recycling of urban land and first generation suburbs, the trends towards renovation and rebuilding to use existing land and infrastructure will only increase. It is clearly important to address the decisions made in the design and construction of buildings that will allow the recovery of valuable resources that will be generated from building removals in the 21st century and beyond.

The economics of building-related debris disposal or recovery are driven by the relative and highly externalized costs of local debris landfill tipping fees and the presence of alternative markets for recovered materials. Two other very important factors are the labor costs and speed of the disassembly process itself. The efficiency of the deconstruction affects the direct costs of labor and equipment and also affects the time costs of a project where building removals are integral to new construction on the same site. Herein lies the opportunities and challenge for DfD. Of all of these factors, the efficiency of the deconstruction process and the cost-effectiveness of materials recovery with highest reuse or recycling value are most influenced by the designer, the architect and engineering team that determines how the building is to be assembled. These designers must understand how their decisions impact disassembly and reuse. The choices and specific uses of materials, the connections between individual materials or components, the inter-relationships of building elements, the designs of spaces and whole-building structure, and even the ability to "read" the building are within the designer's control.

Lessons learned from the deconstruction of older buildings – well-known to practitioners in the field – include: the prevalence of materials that later became environmental hazards for workers and for disposal; the entanglement of HVAC, electrical and plumbing systems within walls, floors and ceilings, that impedes the separation of building components; the use of connectors that are inaccessible and cause damage in the process of separating materials; the weakening and de-stabilization of a building during the deconstruction process; matching the scale of the capabilities of a human laborer to the scale of building components; and how the building assembly process may render materials un-reusable or un-recyclable via drilling, cutting, and use of binders, adhesives, and coatings - especially hazardous materials.

Buildings designed for deconstruction will include the dis-entanglement of systems, and reductions in chemically disparate binders, adhesives or coatings - or thermal / chemical /

mechanical means to better separate constituent materials. Ideally, the problems of maintaining as-built drawings will be overcome by the ability to visually understand the building's construction with minimal intrusion. This building transparency will in turn facilitate building engineering surveys to plan the deconstruction process. Components and materials will have a durable label like consumer product labels that list the materials' composition. This information will reduce uncertainty of planning for reuse, recycling, construction and demolition landfill disposal, or hazardous waste disposal. These buildings will have self-supporting and self-stabilizing components, component accessibility designed in, and built-in tie-offs and connection points for workers and machinery. Most importantly, buildings that facilitate reuse and recycling will use non-hazardous materials, bio-based materials, high quality and highly recyclable materials.

Design for deconstruction offers possibilities for the design of buildings that will tighten the loop of materials-use in building, and help make the transition towards minimal virgin materials use, and a cradle-to-cradle building industry instead of the dominant paradigm of cradle-to-grave. To use a spiritual metaphor, buildings would have karma, such that their spirit (materials) would be reincarnated in future lives, with designs incorporating good karma (design for deconstruction) being more enlightened (transferring materials in valuable form to the next life-cycle). Two notable examples of recently constructed commercial buildings in North America that relied heavily on recovered materials and were also designed to facilitate future materials recovery are the Phillips Eco-Enterprise Center, Minneapolis, MN, and the C.K. Choi Building at the University of British Columbia, Vancouver, BC.

STATEMENT OF THE PROBLEM

The current state of deconstruction is severely limited by numerous factors. The main obstacles can be categorized as costs and time, with these being interrelated. The main opportunity factors for deconstruction are the prohibitive aspects of building materials disposal and the value of recovered materials in environmental and economic terms. Related to the economic costs / benefits of recovered materials are the quality of materials, either for high-quality reuse and economic recycling, hazardous materials, and components and materials that quickly become obsolete, or are unfeasible to process for reuse or recycling. Last but not least, buildings in modern society are not typically *designed* to be deconstructed.

There are many efforts to redefine production and achieve "eco-efficiencies" for consumer products through dematerialization, environmental management, design for environment, design for disassembly, and design for recycling. The design, construction, and maintenance characteristics of buildings are much different than consumable goods. Buildings are expected to have much longer lives, are greater capital investments, and involve a multiplicity of actors in design, construction, regulation, financing, insurance, maintenance, repair, occupancy, and ownership over time. Housing is often seen as a psychologically and culturally more significant artifact than an automobile for instance, although some automobiles might cost more than a modest home. The perception that housing should be malleable for adaptation and disassembly carries the perception of instability, incongruent with the notion of "home as castle." Housing in fact does share many characteristics of consumable products depending upon the culture and urban location. According to Nakajima and Futaki, the average design life of wooden residential houses in Japan is about twenty-five to thirty-five years and the average actual life cycle is fourteen to seventeen years (Nakajima and Futaki, 2001). Changing cultural expectations, economic conditions regarding land use, and technological obsolescence, especially in regard to the energy-efficiency, are key functional and environmental stresses that cause the removal of buildings from use.

Buildings also have public impacts by their creation of urban patterns such as the walls of urban streets and squares. The realization that these urban patterns, some established over generations, can be radically altered by the removal of buildings inevitably comes as a visceral shock when it occurs. Yet it does occur, and the lack of acceptance of the economics and fluidity of land uses in modern society has precluded extensive research into the realities of the need for design for deconstruction. While sustainable buildings should be designed for longevity and durability, this does not preclude the need for urban land-use diversification and flexibility via adaptation and deconstruction as well. On a global basis, transportation energy use impacts, sprawl patterns of land development, and the energy expenditure to operate buildings all told have greater environmental impacts than the use of the materials in construction and resultant waste. Therefore, design for deconstruction is an important means to facilitate the resolution of these problems as much or more than solely to reduce building-related materials waste. As an example, the ability to upgrade electrical and lighting systems in a commercial or institutional building as more energy-efficient fixtures and lamps become available might be a more significant advancement in sustainable building practices than the reuse or remanufacturing of the obsolescent fixtures or lamps themselves. If a sustainable built environment maximizes the ability to operate in a hierarchical and flexible manner, buildings will need to be multi-faceted storages of energy and materials, able to work within temporal and cultural currents of economic, social and natural environmental conditions.

A principle consideration for building adaptation is the spatial and temporal shearing inherent between the systems and materials in the building (Brand, 1994). This includes accessibility of components without conflicts between shorter-lived and longer-lived components. A key consideration for the end-of-life deconstruction of buildings is the connections between components, separation of materials into their base form, and the removal of nails, staples, paints. The contamination of base materials by the connecting devices, coatings, treatments, and the time requirements and damage resulting from the re-separation for salvage and reuse often make deconstruction extremely un-economic in a high-labor rate market.

One of the impediments for design for deconstruction is if the addition of elements that facilitate deconstruction cause an increase in first-costs of construction and clearly do not result in any near-term payback for the resultant future avoided costs or recovered value. In order for design for deconstruction to be effective, it will optimally not cause an increase in first costs and will be compatible with energy-use and other operational efficiencies. An example of an individual element that costs more than traditional practice but facilitates adaptation and energy-efficiency is raised flooring systems. Deconstruction is facilitated with this system by eliminating ductwork and placing modular re-configurable wiring in a more accessible location in the floor plenum rather than an overhead plenum, and allowing the ceiling to be eliminated altogether, providing better access to lighting systems.

The single greatest criteria for the success of design for deconstruction is that the cost of the final gross deconstruction costs do not exceed the avoided disposal costs, plus the reuse or recycling value of the components and materials, plus the removal costs of a building not designed for deconstruction, (Billatos and Basaly, 1997). The economic feasibility of deconstruction in low-disposal costs regions is therefore dependent upon the highest and best reuse or recycling value of the recovered materials and the efficiency of the deconstruction process, i.e. labor costs.

GOALS OF DECONSTRUCTION

Deconstruction serves as a means to an end, its purpose is the recovery of building elements, components, sub-components, and materials for either reuse or recycling in the most cost-effective manner. Within the theme of design for deconstruction there is a distinction between designing for reuse and designing for recycling based upon components and types of materials used in a building. Deconstruction per se implies a high degree of refinement in the separation of building components. If a building were deconstructed to some hypothetical maximum it would result in materials and components down to the level of their original form before construction. It is not practical to approach design for deconstruction at the whole-building level in this manner as some components, such as a window for instance, may be obsolete by the time the building is deconstructed and undesirable for reuse as exterior windows.

Deconstruction is also difficult to integrate into new construction. Removing materials from an existing building to integrate into new buildings requires that the demolition and building contractors become materials suppliers. In addition to the demolition and construction processes they must address issues of materials inventory and storage, additional handling and transportation requirements, and integrating what is in effect a stock component into designs where the preference might be for custom-designed components. Quantities and quality of recovered materials are a factor when a design must either match the available sizes and quantities of recovered components, or face the uncertainty that sufficient and appropriate recovered components will be found to match the design. The cost-effectiveness of recovering varied and small materials such as wiring, nails and bolts might also be negative. An exception is copper wiring.

In practical terms, some materials are not readily reusable but can be recycled in a cost-effective manner. Based upon this perspective, it is possible to approach design for deconstruction as “hierarchical design” including; 1) design for reuse, 2) design for remanufacturing, and 3) design for recycling. Primdahl uses the term “embodied energy maintenance,” or retaining the maximum amount of net embodied energy based upon each type of component or material within the structure and the available infrastructure for recovery (Primdahl, 2002). The constraints on this optimization include the scale of buildings and components, temporal forces between differing building elements, functional and service requirements of the building, relative impacts of building elements in terms of first costs and life-cycle costs, the physical forces at work in a building, the chronology of construction and hence deconstruction of the building, and the components and raw materials of the building.

As an example of the complexity of optimizing design for deconstruction, the fewer number of components to a building would appear to be highly preferable. However, this criteria alone is insufficient. A very few, and hence large, components that required expensive and large equipment to maneuver and were not readily reusable as is, due to the difficulty in matching the component to a new use, might not necessarily be cost-effective. If a material such as steel is used which is highly and effectively recycled, a highly refined deconstruction process is relative in this case since a building largely comprised of steel could be mechanically demolished and the steel separated from the heterogeneous debris through the use of magnets. The separation process after demolition supersedes the requirements to facilitate separation in the demolition phase.

Another complexity to design for deconstruction is that the energy costs of operating a building are a high proportion of the total costs of the building over its life, including construction and deconstruction. Designing for deconstruction in a manner that compromises the energy-efficiency of the building would not result in an environmentally or economically effective building over its life-cycle. An example of this situation might be eliminating moisture and air filtration chemical sealants to facilitate mechanical disassembly, but not designing a substitute means to reduce moisture and air penetration through the building envelope. A substitute for extensive sealants and adhesives in a roof system might be either mechanically fastened single-ply roof on a flat roof, or high-slope roof design to facilitate rainwater runoff through gravity. In both cases mechanical forces are used as a substituted for chemical sealants, without loss of building envelope integrity.

The design for deconstruction problem analysis for a building might be facilitated by asking questions such as:

- What parts of the building support other parts ?
- What parts of the building are self-supporting ?
- Where do specialized service inputs and outputs (telecommunications, electricity, water, gas, wastewater, supply and exhaust air) occur and how are these flow mechanisms constructed ?
- What parts of the building are subject to the most stresses from climate?
- What parts of the building are most subject to wear from human use and change from aesthetic preference ?
- What parts of the building are most subject to alteration based upon functional, economic, life-expectancy, or technological requirements?

- What parts of the building are comprised of components and sub-components based upon a complex set of functional requirements and what parts serve only one function and hence are comprised of relatively homogenous materials ?
- What parts of a building pose the greatest worker hazards in disassembly?
- What are the functional sizes of the principle elements and components of a building?
- What are the most expensive elements of a building, which have the highest reuse and recycling value and which impact the life-cycle efficiency of a building the most?

Currently, deconstruction feasibility will be heavily based on economic considerations with environmental considerations a secondary concern. The economic drivers for the future recovery of construction-related debris will be bans or economic penalties on the disposal of construction-related debris, constraints on virgin materials, and a paucity of landfill space. If manufacturer responsibility regulations expand to the building industry and its many associated products, design for deconstruction will be an integral part of enabling this process. The steel industry and to a lesser extent, the concrete industry, have established recycling infrastructures. Increasingly, other building products industries such as carpet, drywall, and acoustic ceiling tile manufacturing are developing recovery infrastructure. Deconstruction in the current state of the building industry has both opportunities and constraints as illustrated in Table 1.

Table 1 - Opportunities and Constraints of Deconstruction

Opportunities	**Constraints**
Management of hazardous materials	Increase worker safety/health hazard
Reduction in landfill debris	More time required
Economic activity via reused materials	Site/storage for recovered materials
Preservation of virgin resources	Lack of standards for certain recovered materials reuse
Removal of inefficient/obsolete structures	Lack of established supply-demand chains
Reduction in site nuisance compared to demolition	Buildings not designed for deconstruction and high variability in assembly techniques
Quality or aesthetic appeal of historic components of materials (ex., fireplace mantle, heart pine lumber)	Labor intensity in terms of skills and degree of materials processing, particularly removal of lead-based paint

Based upon possible conflicts between these factors it is important to consider the goal(s) of deconstruction when adding design for deconstruction to the many other aspects of sustainable building design and construction. Some goals for design for deconstruction might be:

- Rapid removal of building from building site.
- Reduction in environmental, health and safety stresses for workers.
- Easy access to components and materials, preventing damage in the deconstruction process.

- Reducing the costs of tools and equipment, for example scaffolding and fall protection equipment, specialized tools such as nail-kickers, and use of specialized operators or attachments for heavy equipment to facilitate the process.
- Eliminating the wastes by-products from the process.
- Materials recovery with high efficiency of reuse and recycling, i.e. requiring minimal additional processing for the highest return on investment in the deconstruction process.
- Eliminating toxicity in building materials which impacts responsible reuse and disposal and reduces reuse/recycling opportunities
- Increasing the longevity of a building such that deconstruction is actually less likely to occur via the inherent adaptability that design for deconstruction will convey upon the building.

PRODUCT DESIGN FOR DISASSEMBLY

Design for disassembly has been well-studied in the so-called consumer products industry, for example, for automobiles and computers. The automotive industry has been engaged in design for environment for some time, for example, General Motors, Chrysler and Ford formed the Vehicle Recycling Partnership in 1994 to develop means to recover materials from automobiles for reuse and recycling (Billatos and Basaly, 1997).

Examples of design for disassembly tools for products that have been recently developed include: BDI Design for Environment - Boothroyd and Dewhurst, Inc.; Ametide - University of California at Berkeley; DFR-Recy - Helsinki University of Technology; EUROMAT - Technical University Berlin; LASeR - Stanford University; MoTech - Technion University, Israel; ReStar - Green Engineering Corporation (Otto and Wood, 2001). The number of tools and disparate locations of their development indicate a widespread interest in solving the problems of consumer products designed for disassembly.

One tool is the End of Life Design Advisor (ELDA) developed by the Manufacturing Modeling Laboratory at Stanford University, which is meant to inform the design of products based upon their end-of-life (Rose, 1999). The tool is meant to help determine the paths of materials upon disassembly, either for reuse, recycling, disposal or hazardous materials management.

A list of key characteristics used in the ELDA to determine a product’s disassembly and materials reuse/recycling potential provides generic guidelines for design for deconstruction as a form of design for disassembly. By testing the ELDA on a series of consumer products it was found that the number of parts, number of materials, level of cleanliness, design cycle, technology cycle and replacement cycle are important factors for end-of-life. Size, number of modules, hazards, wear-out life, reason for obsolescence, and functional complexity were not found to be critical to prediction of end-of-life strategies (Rose, 1999). The key characteristics used to measure disassembly potential are noted below.

Critical Factors for End-of-Life

- Number of parts
- Number of materials
- Cleanliness of the product - amount of dirt accumulated by product
- Design cycle - time between new designs
- Technology cycle - time that product will be cutting edge before new technology makes it obsolete
- Replacement life - time that average user upgrades product

Non-Critical Factors for End-of-Life

- Size
- Number of modules
- Hazards and hazardous materials - components that need to be removed before further recycling
- Wear-out life
- Reason for obsolescence
- Functional complexity - high level of dependence between parts with multiple functions (Rose, 1999)

Buildings are large and subject to gravitational stresses that differ from most consumer products. The non-critical factors of size and hazards and hazardous materials for consumer products are more critical for buildings. Buildings also have the distinction of being fixed in a bio-climatic location, unlike other consumer products. For any given location and type of building there are inherent functional, cultural, climatic, geological and ecological forces that suggest certain forms, structure, envelop designs, and materials. Buildings are also subject to the depredations of weather and to the stresses of repair, maintenance and alterations that occur over time with differing ownership or functional needs. Because sustainable architecture design will have unique qualities per the location and building type, it follows that design for deconstruction would be also be specific to each building if there is consideration for sustainable design and cultural appropriateness.

Designing to allow a more rapid life-cycle for components that tend to become obsolete faster is one strategy proposed to maintain the quality and efficiency of consumer products (Sindjou, 1999). A key philosophical question is whether buildings should be intentionally designed for deconstruction as a product is designed for disassembly in order to reduce the waste and inefficiency that occurs from depreciation in the performance of the building, especially regarding energy use and technology-related components. While the remanufacturability and recyclability of components and materials would remain high with a rapid turnover it is not clear whether this would be the most environmentally sustainable strategy overall, except for those elements that directly impact the energy-efficiency of a building. Components such as mechanical and electrical equipment that are designed for deconstruction would possibly increase the efficacy of maintaining a building's structure and envelope as long as they do not require extensive modification of the structure and envelope when they are upgraded. In any case, the point of diminishing returns will be reached by upgrading HVAC equipment for instance when the efficiency of the building envelope - as a fixed element - is low, and does not also continue to contribute to increasing the efficiency of the building operation. As illustrated in Figure 4.1, over the 30 years of the projected energy costs for the reference "bad existing" building, the lowest total energy costs will be for an immediate new high efficiency retrofit. A new low-energy replacement building will require more energy initially, but over the next 25 years it will begin to recoup that additional energy by lower operating costs overall. Beyond 30 years the new low-energy replacement building becomes more and more cost-effective. The retrofit option will be much less initial investment but at the 25-year mark begins to become less efficient on a yearly basis. Extending the projections it might be seen that at 50 years, it is appropriate for total life-cycle costs - construction, materials and operation - to completely replace this new low energy-use replacement building, and again at 50-year intervals.

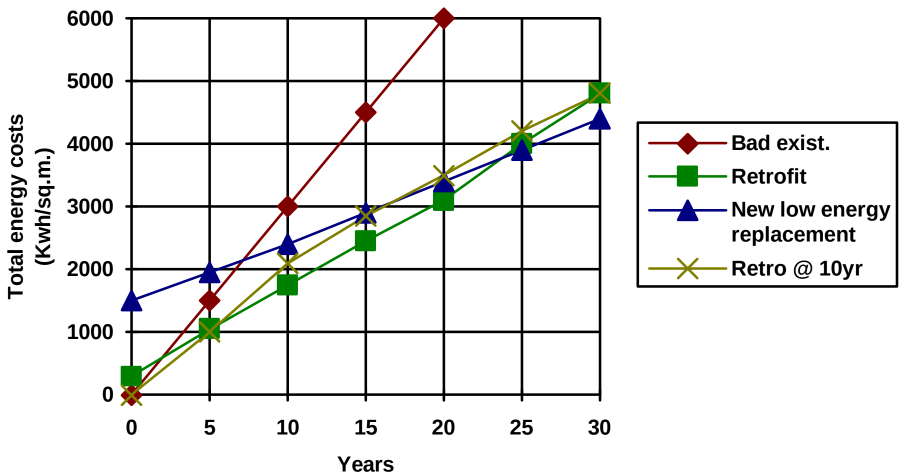

Figure 1 - Life-Cycle Costs Scenarios for an Existing Building (UNCHS, 1991).

This hypothetical replacement cycle of 50 years for an average building is very long relative to any other consumer product but could be confirmed for a specific type of construction through extensive modeling. Some assumptions would have to be made about the increasing speed of technological innovation for cutting-edge building systems such as building-integrated photovoltaics and hydrogen fuel cells. If it is presumed that overall sustainable construction requires maximizing resource-efficiency, then designing for building life-cycles, and achieving near zero-waste in the deconstruction of buildings at the end of this life will be one method for achieving this goal.

LESSONS LEARNED FROM BUILDING DECONSTRUCTION

Product analysis of design for assembly can be accomplished by disassembling products and putting them back together. This method also establishes baseline for the time and difficulty to disassemble a product (Otto and Wood, 2001). Deconstruction can be used in a similar way with the intent to heuristically analyze the critical elements necessary to design for deconstruction.

The approach to design for deconstruction suggested herein is to use the basic concepts of design for disassembly from the product industry combined with a categorization of the generic qualities of a building and its major elements, and lastly to learn from the deconstruction of buildings built in the 20th century. The authors have been involved in the demolition and deconstruction of buildings ranging from large multi-story commercial/institutional buildings, to heavy timber buildings, to light wood-frame residential buildings both pre- and post-WW II. Many themes related to future design for deconstruction were discovered from this field-based research.

Concrete and Masonry Institutional Building

Hume Hall was a 1950's, 133,000 square foot, 4-story institutional building constructed of a concrete floor and column system with a flat concrete roof and built-up tar and gravel roof finish. The exterior and interior walls were infill concrete masonry units and the exterior finish was a double-wythe brick veneer. Windows and glazing were comprised of casement metal frames and aluminum storefront and fixed glazing, respectively. Mechanical and electrical systems were run principally in ceiling plenums formed by suspended acoustic tile ceilings. Interior finishes were comprised of resilient floor coverings, painted concrete masonry, and drywall.

The non-structural process of removal consisted of the recovery of all reusable fixtures and hardware, and the removal and disposal of windows as part of the abatement of asbestos containing caulking materials. The major elements and structural removal was comprised of a partial "stripping" of the brick veneer to separate it from the concrete structure and masonry exterior walls and the mechanical reduction of the predominantly concrete, masonry and steel reinforced structure. The only cost-effective reuse or recycling occurred from the soft-stripping of hardware and fixtures before the demolition process took place. Although the brick veneer was readily separated from the building façade for additional de-mortaring, the mortar itself was cement-based and did not lend itself to hand separation. Considerable costs were avoided by the mechanical reduction of the masonry and concrete materials and removal of reinforcing steel for recycling. Asbestos abatement was a large proportion of removal costs with no reuse or recycling potential.

Design for Deconstruction Opportunities

Masonry construction must use a mortar that facilitates the separation of the masonry back into individual units, i.e. the mortar has different strength than the masonry or other properties, such as a different coefficient of thermal expansion, that can be utilized in a separation process.

Large concrete and steel structures are constructed using mechanical equipment and therefore lend themselves to deconstruction using similar equipment. Mechanical equipment has the capacity to reduce concrete to recyclable form as long as contaminants of interior components, finishes, and thermal and moisture protection systems can be removed cost-effectively. Post and beam and/or flat plate concrete systems allow for maximum flexibility in separating all non-cementitious materials from the concrete and steel reinforcing structure of the building. Concrete is inflexible for reuse but readily recyclable, therefore the ability to recycle concrete should be prioritized over the concept of large concrete components' reuse.

Light Wood-Framed Residential Structures
More than nine residential structures have been deconstructed by the Center for Construction and Environment in the past four years. These structures were light wood construction on wood floor structures raised on piers. Walls were light-wood framing with drywall, wood lath and plaster, wood interior finish, wood exterior finish and combinations of asphalt shingle and metal roofing. Light wood framing is also known as "stick-framing" which indicates the method of construction and hence most appropriate method of deconstruction, i.e. stick by stick. As wood has considerably more value in reuse than in recycling and mechanical equipment is difficult to use at a "stick-by-stick" level of disassembly, this type of structure lends itself to hand deconstruction.

These structures were typically deconstructed by removing all interior non-structural elements, layer by layer, removing the structural elements starting with the roofs, then the load bearing walls, then the floor structure and foundation. Because workers are within the building at every step of the process, the building must be structurally sound at every stage of the deconstruction. Structure versus non-structure, sizes and weights of components and materials, and the height of exterior and interior elements relative to human scale, are key elements that control the deconstruction effort.

One of the most onerous aspects of modern architecture and construction readily found in most US buildings built before 1970 or so is the presence of lead-based paint (LBP) and asbestos containing materials (ACM). At a secondary level, PCBs, mercury, and ozone depleting chemicals are also hazardous materials that greatly complicate the recovery of building materials for reuse and recycling while not endangering workers and/or expending large sums to separate these materials from potentially reusable or recyclable base materials or sub-components. The regulatory requirements for worker protection and disposal of hazardous materials were a large cost for the deconstruction of older wood-framed residential structures, and the presence of lead-based paint is an impediment to wood reuse.

Design for Deconstruction Opportunities
High-slope roofs are problematic for deconstruction working platforms, therefore the use of ridge caps that are easily removable and allow access to the roof structure for tie off, or are designed to support the requisite load for a worker lifeline for roof finish and sheathing removal, would facilitate both roof repair and ultimate deconstruction.

Panelized roofs that allow the mechanical removal of large sections of roofs for processing on the ground would preclude the need for fall protection and risks and added time involved from working at heights.

Light wood frame construction and the properties of wood allow for drilling and cutting small sections from walls and roof structural members to run electrical conduit and plumbing fixtures. This has the unfortunate consequence of creating a layer of materials that can be embedded throughout wall cavities. In order to remove the materials, they must be cut, unscrewed, pulled and collected together. Ceiling mounted HVAC and electrical systems require ladders, scaffolding and considerable mobility to access and remove. The less of these interstitial components the better, therefore designing to consolidate mechanical and plumbing systems into fewer locations, surface mounting of electrical and telecommunications systems in wiremolds, and sectionalized gang units of electrical and telecommunications wiring with snap fitting or other screw-in connector would allow for adaptation and removal.

A notable impediment for deconstruction was often damage to components by water leakage and wood-boring organisms over time. This damage weakens the building structure and reduces the value of the recoverable materials. If nothing else design for deconstruction would also add impetus to design for durability and solve the problem that it is of little utility to efficiently disassemble a building if the materials themselves have not been protected from decay.

Although chemical sealants, coatings and adhesives add water protection and strength to building materials, they are significant prohibitions to hand deconstruction. From an environmental perspective, these types of additives should be eliminated with the recognition that mechanical methods of water protection and connections will require additional design and construction effort. The resulting reduction in performance, if one occurs, can be overcome by the ease of disassembly (by using screws and bolts for instance) for replacement and repair of components and sub-components.

Large Wood Post and Beam Structure

The Unitarian Church was a 5,000 square foot structure with slab-on-grade foundation and floor, large glu-lam arch structural frame with structural 2”x 6” tongue and groove roof planking, built-up tar and gravel and asphalt shingle roofing. The building wings’ roof structures were long span glu-lam beams supported by steel columns at one end and the sides of the glu-lam arches at the other end. Bolts were used at the connections between columns and slab, between beam and column, beam and arch, and between arch and slab and between the arch members at the ridge point. Glazing was large sliding glass doors or fixed glass, and non-structural exterior and interior partitions were comprised of light wood framing and either wood paneling or drywall. Wiring and ductwork was placed into framed ceiling cavities or interior partitions.

Upon hand removal of interior finishes and partitions and ductwork, the roof structural planking was removed by hand as well. The side wings’ glu-lam beams were unbolted and removed by a crane as were the structural glu-lam arches. The remaining debris and the concrete slab was removed by machine labor and crushed for disposal and recycling, respectively.

Opportunities for Design for Deconstruction

This building exemplified many concepts of design for deconstruction. The structural arch frame integrated both post and beam into one member that in turn was bolted at the floor structure and to each other. The horizontal beams were also bolted, as were the steel columns. The central arched section of the building was self-supporting and allowed the wings to be removed as separate elements. Structural roof planking combined structure with roof exterior sheathing and interior finish on the underside, greatly reducing materials used and layers of additional materials removal to separate the wood members. The mounting of mechanical and electrical ductwork and wiring within only non-structural wall or ceiling cavities allowed for selective demolition of these low-value components. A flat roof system on the wings of the building acted as a working platform to great effect for roof removal, whereas the high-slope roof portion presented greater difficulty. Conversely, the flat roof system used a built-up tar and gravel roof membrane over rigid insulation which was the epitome of heterogeneous, chemically bonded and heavy-weight materials that do not facilitate removal or cost-effective separation and recycling. Given the overall time and effort for each type of roof, the high-slope roof was a better option for deconstruction. A monolithic slab-on-grade foundation integrated foundation and floor structure at the grade level, facilitating ease of mechanical scraping to remove contaminating debris and then crushing the homogenous concrete element for recycling.

PRINCIPLES OF DESIGN FOR DECONSTRUCTION

According to Rose, et al, two of the most critical factors in predicting the end-of-life path of products are replacement cycle and technology cycle (Rose, 1998). According to Billatos and Basaly, the main criteria for examining a product for increasing its assembly efficiency is to reduce the number of parts and to reduce the amount of time required for assembly (Billatos and Basaly, 1997) According to Otto and Wood, critical factors in design for disassembly are the number of tasks, number of tools, and the time or degree of difficulty of the tasks (Otto and Wood, 2001). Each of these factors also has relevance for building disassembly.

Time is the single most important factor for building disassembly, unless the entire building can be removed to a separate location for disassembly, but this relocation can cost as much or more than the entire deconstruction. One alternative to the problem of demolition and new construction occurring under one contract, necessitating the fastest building removal possible, is a separate pre-construction demolition contract with a longer time frame. When demolition or deconstruction begins, time is a factor of the number of tasks, and difficulty of tasks. Difficulty includes the number of tools, height, safety precautions, etc. Replacement cycles and technology cycles generate conflicts between faster and slower cycling components and also count as critical concerns over the adaptive life of the building, but less of a concern for a whole-building removal.

Based upon generic elements of structure, building envelope, and services - including roofs and walls, and service systems such as the provision of electricity, conditioned-air, water, telecommunications, and gas, and the removal of wastewater and exhaust air - a building could be designed first to isolate these major elements from one another. A building designed for deconstruction for the purposes of first removing a building from a site might separate these major elements, i.e. roof, walls and floor/foundation as modular and pre-fabricated construction techniques do in the construction phase. Dealing with the material types and a sub-level of design for reuse, remanufacturing, or recycling, and other sustainability concerns such as human health and environmental impacts from materials and building energy-efficiency become mitigating factors to this level of building element separation.

On a fundamental level wood is a highly preferable material in design for deconstruction since it is flexible for both reuse and recycling, a "natural" material, and can be readily connected using interstitial connecting devices such as bolts. Steel is also a material with great utility for design for deconstruction due to its ease of recycling through a thermal process and ability to span large distances with less mass of material than concrete for instance. Steel also lends itself to post and beam construction via its high tensile strength. Of the other major material, concrete, its greatest utility in design for deconstruction is its durability as a structural material and its ability to act in both compression and tension, with reinforcing, for forming integral floor and ceiling elements that can also act as building envelope and finish. Concrete already is a relatively highly recycled material but is not easy to recycle when it is contaminated by other building components. Unless these components and sub-components have their own inherent value apart from allowing the concrete components to be recycled, it is not cost-effective to remove them for the purpose of recycling concrete components, unless mechanical means are used.

One means to design for disassembly is to expedite the understanding and viability of a disassembly sequence for either building elements or the entire building. The simultaneous creation of a deconstruction plan along with the construction plan and labeling of components for their constituent materials, similar to plastic products label numeric codes to indicate the type of plastic will provide directions to the deconstruction contractor for the disposition of materials. As with building energy management systems with Web based control and monitoring software, as-built drawings, deconstruction plans, detailed materials inventories and make-up can all be recorded and maintained for a building. This concept can go so far as to install this information on a computer built into the building itself.

The ability to pre-market materials for reuse and recycling based upon known types and quantities provides an economic incentive for the deconstruction process. It also allows for prioritizing materials disposition in the order of reuse, remanufacturing, recycling or disposal, depending upon local materials, reuse, remanufacturing and recycling infrastructure, with a better ability to calculate costs and benefits. An upfront deconstruction plan also allows for planning the management, scheduling and safety requirements of the deconstruction process. Borrowing from Fletcher's hierarchy of System, Product and Materials for DfD, this hierarchy can include process as well as physical elements (Fletcher, 2000). Within each level of the building design and element hierarchy, the deconstruction process is the first step in the materials disposition process, and therefore sub-levels have an appropriate path depending upon a materials management hierarchy.

An element is defined as a major building part such as roof, vertical structure, wall, floor or foundation. A component is defined as the next level of non-structural building part such as thermal or moisture protection systems, windows and other systems such as the heating and cooling systems. A sub-component is a breakdown of a component into its smaller pieces such as the duct system of a heating and cooling system, the hardware for a door unit, or the sash of a window unit. A material is the constituent material from which all other parts are made, such as plastics, metals, wood, and masonry. Added to these physical definitions is the process of design and construction as independent levels of information that not only dictate the types of materials or connections, but can facilitate deconstruction through information management and major architectural decisions such as the slope of a roof.

An illustration of a design for deconstruction hierarchy is illustrated below.

- **Design**
    - Minimize building depreciation from poor energy-use, climatic and materials performance by performance-based materials selection
    - Substitute mechanical/gravity-based design for chemical-based design or chemical that break down when another chemical or heat is applied.
- **Construction**
    - Record as-built conditions
    - Create deconstruction plan based upon construction process
- **Elements -** design for modular and panelized elements that are readily fit into common dimensional standards and possible de-panelization
    - Principle DfD sub-goal - Reuse
- **Components** - design for ease of separation from the next higher building level, i.e. elements
    - Reuse
    - Remanufacture
- **Sub-components** - design for separation from component level
    - Reuse
    - Remanufacture
- **Materials** - design for separation from sub-component level and as homogenous materials
    - Remanufacture
    - Recycle
    - Bio-degrade

As a basic principle, matching a level of complexity and invested energy, components are designed for reuse and remanufacture, sub-components are designed for reuse and remanufacture, and materials are designed for remanufacture, recycling and bio-degradation. These hierarchies would be driven primarily by the constituent materials at each level, but a high embodied energy component should require as little additional energy and costs as possible for its continued utility.

Table 2 Relative Percent of Building Components by Different Measurement Systems (Adapted from Marshall Valuation Service, Marshall and Swift Publication Co., Los Angeles, CA. 1995 and *UNCHS, 1991)

Category	Percent of completion cost total	Percent of cost total	Percent of embodied energy*
Sitework, masonry, and concrete	12	7.0	14.6
Wood	21	17.7	9.8
Windows and doors	2	4.0	6.4
Thermal and moisture protection	10	12.8	20.0
Plumbing, electrical, and mechanical equipment	23	18.0	27.3
Interior finishes, hardware, and cabinetry	30	22.9	9.3

Table 2 is meant to illustrate well-known considerations of the cost-effectiveness of deconstruction based upon considerations of mass and embodied energy of typical building elements, components and materials. Non-structural “soft-stripping” greatly reduces the worker safety and equipment considerations and increases the cost-effectiveness of deconstruction. Wood is a high proportion of the percent of completion and cost of an “average” new building but has low embodied energy. Thermal and moisture production is a relatively low percentage of completion of a building but much higher in terms of embodied energy due to the types of materials used. Plumbing, electrical and mechanical equipment are a high percentage of completion and also a high percentage of embodied energy. Interior finishes, hardware and cabinetry are the single greatest percentage of completion and costs and yet relatively very low in embodied energy principally due to the much lower mass of these types of components in a typical building. At the whole-building level, high embodied energy components such as thermal and moisture protection and mechanical, electrical and plumbing systems would not only be subject to more rapid functional, climatic and technology life-cycle stresses but inherently are environmentally and economically valuable components to be targeted for design for deconstruction. Interior finishes also have a high value to mass ratio making them an obvious target for non-mechanized, i.e. high labor rate, removal for remanufacturing and recycling. A confirmation of this type of analysis, looking at major elements of the building and deconstruction constraints is presented below in Table 3.

Table 3 Design for Deconstruction Analysis of Wood-Framed Residential Building
Assuming wood windows and doors, wood light-frame construction, drywall interior finish, asphalt shingle roofing, wood floor structure and masonry or concrete foundation, wood floors, H = high, M = medium, L = Low, Y = yes, N = no, Value = potential revenue from reuse or recycling, Mass = higher mass avoidance of disposal, Ease of removal = relative less time, equipment

Element	Internal cycling rate	Value	Embodied Energy	Mass	Ease of removal	Structure
Windows/Doors	L	H	H	L	M	N
Appliances	H	L	H	L	H	N
M, E, P Equipment	M	M	H	L	M	N
Cabinetry	H	H	H	L	H	N
Int Finish	H	M	M	L	H	N
Duct, Pipe, Wire	**L**	**L**	**H**	**L**	**L**	**N**
Int Wall/Ceiling	L	L	L	L	M	Y
Roof	L	H	L	M	L	Y
Ext Wall/Structure	L	L	L	H	M	Y
Floor/Structure	L	H	L	M	M	Y
Foundation	L	L	L	L	H	Y

Based on this simple residential building analysis, the inherent deconstructability of most non-structural elements indicates fewer impediments to deconstruction for these components in traditional design and construction methods. The clear exception is duct, pipe and wiring. The low mass of a very dispersed elements with a high degree of entanglement and low reuse value all combine to make these components an impediment for selective disassembly and whole-building deconstruction. For this type of building, exterior and bearing walls have a high mass but low reuse value and medium level of effort required for removal within a sequence requiring the removal of the roof element first. One indicator from this analysis is that bearing wall construction is not conducive to cost-effective deconstruction. The roof element is relatively independent, yet requires additional time and equipment due to height

General Design Concepts

A list of design concepts and components for facilitating deconstruction of buildings is provided below.

- Compressed wheat-straw interior partition panels with integral paper facing are an example of self-supporting elements that can be disassembled as a unit and have the additional benefit of being a homogeneous and natural/recyclable material as a substitute for drywall and light wood 2”x 4”framing.
- Bolted roof trusses and offset tie-downs or roof to wall connectors that are attached at a point away from the actual point of contact of the roof structure to the wall. This would require an additional element such as a knee-brace to bridge between the two elements and increase the distance between the points of connection to roof and wall, but allows for ease of access to the connectors.

- Platform-type wall construction whereby the walls sit on top of the floor structure and do not extend through the horizontal plane of the floor structure and the floor above rests on top of the wall element. Separating the plane of the top and bottom of the wall from the plane of the floor structure facilitates mechanical separation and structural stability during the deconstruction process. Pre-cast concrete floor panels act in this manner.
- Light-weight materials for instance integral and modular elements combining finish, thermal and moisture protection, and structure, for roof structure, sub-structure and finishes to reduce the stresses on the lower portions of the building and reduce work at height and use of equipment. These impediments of height can be somewhat mitigated by integral worker stations and point of connections for equipment and handling. An example of this principle would be structural insulated panels (SIP). Substituting a glued and heterogeneous SIP system for individual wood roofing members must be weighed against the potential for reuse and recycling of the panels.
- Simple consolidation of plumbing service points within a building has the benefit of reducing the length of lines, but also reduces the points of entanglement and conflict with other elements such as walls and ceilings/roofs.
- A separation of structure from enclosure, will greatly facilitate adaptation and deconstruction however it is important to remember regional climatic forces, whereby a building in a temperate climate will not be as penalized by a possible variety of enclosures and loose-fit as will a building in a high heating load climate.
- Hazardous materials such as asbestos and lead-based paint have been outlawed. The next generation of these materials will include fibrous insulations, chemical treatments for wood, and many synthetic materials used as sealants, caulking, coatings, binders, and adhesives. All materials should be examined using a precautionary approach to eliminate possible toxicity or future regulatory constraints to their use and disposition.
- Nails and bolts have appropriate uses as per the type of connection and size of the members. A variety of nails in one building causes the requirement for multiple tools for removal. A mix of bolts, screws, nails requires constant shifting from one tool to the next. Fewer connectors and consolidation of the types and sizes of connectors will reduce the need for multiple tools and constant change from one tool to the next.
- Long spans and post and beam construction reduce interior structural elements and allow for structural stability when removing partitions and envelope elements.
- Doubling and tripling the functions that a component provides will help "de-materialize" the building in general and reduce the problem of layering of materials.
- Separating long-lived components from short-lived components will facilitate adaptation and reduce the complexity of deconstruction, whereby types of materials can be removed one at a time, facilitating the collection process for recycling.
- The requirement for access to connectors is a functional requirement that in turn dictates a building aesthetic. Access areas for maintenance are well-understood

but little dealt with even in conventional design, due to the need to maximize habitable and income-producing square footage, and maintain a highly refined aesthetic. The design for deconstruction aesthetic is modeled in the "high-tech" architecture aesthetic.

- Elimination of caulking and sealants and high-tolerances in the connections can be offset by the ease of removing components for repair and replacement, and designing in durability, using mechanical instead of chemical-based water protection.

CONCLUSION

Design for deconstruction has much to learn from product design for disassembly. It also has unique qualities based on buildings as significantly different artifacts than consumer products. Buildings have much greater life cycles than consumer products and engage a larger number of actors over their lives than consumer products. It is not well-understood whether design to facilitate a more rapid turnover, if not for whole buildings, then for major energy-use and technology-oriented components of buildings will inherently make them more efficient to operate and therefore assist in maintaining their long term value. The commercial building industry has already adopted many techniques to allow for internal adaptations with reduced waste and costs in order to meet service sector demands for technological and economic flexibility. Design for deconstruction can be studied from the perspective of deconstruction of existing buildings and the lessons learned from this research can be used to design for deconstruction in the future.

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